Engineering evaluation of fragmental rockfall hazards

Evaluation des risques d'éboulements fragmentaires

O.HUNGR, Thurber Consultants Ltd, Vancouver, British Columbia, Canada
S.G.EVANS, Geological Survey of Canada, Ottawa, Ontario, Canada

ABSTRACT: Small scale rockfall is a common process on mountain rock slopes. The process impacts upon transportation facilities and buildings, sometimes with fatal results. Methods currently available to delineate areas subject to rockfall impact include geological, empirical and analytical methods. These methods are examined with reference to rockfall sites in southwestern British Columbia. Preliminary results of an analysis using a lumped-mass model developed by the authors are presented for three case histories.

RÉSUMÉ: Les éboulements rocheux de petite envergure se produisent fréquemment sur les pentes rocheuses des montagnes. Ce phénomène a un effet sur les installations de transport et les édifices, effet qui peut d'ailleurs parfois s'avérer fatal. Parmi les méthodes permettant actuellement d'identifier les régions sujettes à l'effet des éboulements rocheux se distinguent des méthodes de nature géologique, empirique et analytique. On procédera à l'examen de ces méthodes en faisant allusion aux endroits dans le sud-ouest de la Colombie-Britannique où se sont produits des éboulements rocheux. Les résultats préliminaires d'une analyse effectuée à l'aide d'un modèle de type "lumped-mass" mis au point par les auteurs, sont présentés pour trois cas ponctuels.

INTRODUCTION

Small scale rockfall is a common mass movement process on steep rock slopes, especially in mountainous regions. In the Canadian Cordillera rockfall frequently causes costly blockages and damage as well as injuries on roads and railways crossing exposed slopes. Damage to buildings is much less frequent but it does occur with dramatic and often tragic consequences as described below. Further, as human activity increases in mountainous regions the potential of rockfall impact upon structures has become an important part of physical facilities planning. A need exists to delineate and exclude zones from development which are subject to potential rockfall impact.

In recent years there has been substantial interest in the use of empirical (e.g. Lied, 1977) as well as analytical methods (e.g. Piteau and Clayton, 1977; Azimi et al., 1982; Falcetta, 1985; Descouedres and Zimmermann, 1987) to delineate areas of potential rockfall impact. This paper evaluates some of the approaches currently available to estimate the behaviour of rockfall based on investigations of some rockfall sites in the southwestern Canadian Cordillera. It presents an analytical model that simulates fragmental rockfall behaviour which is then used to analyse three case histories studied by the authors.

It should be noted that this paper is concerned only with fragmental rockfall, i.e. rockfall characterized by one or several independently rolling, sliding, or bouncing fragments. The process may involve the detachment of rock masses ranging in volume from several cubic metres to several tens of thousands cubic metres. Fragmental rockfall is distinguished from rockfalls involving the mass flow of fragmental rock since the mechanics of the two processes are different.

CHARACTERISTIC ROCKFALL PATH PROFILE

The long term operation of rockfall processes produces talus slopes made up of rockfall fragments beneath the source rockslope. The depositional pattern exhibited in talus slopes reflects certain regularities in rockfall fragment behaviour. An important aspect is the natural "gravity" sorting by size observed by many authors (e.g. Gardner, 1970; Kotarba and Stromquist, 1984). Size sorting contributes an important roughness component to the talus slope surface which becomes the characteristic rockfall path profile for successive rockfalls. A rockfall dominated talus slope exhibits a typical profile as seen in Figure 1. Finer talus fragments accumulate below the apex (Point A) at an angle of approximately 38°. Lower down, the talus angle ranges from approximately 32° to 38°. The lowermost part of the talus deposit contains the largest grain sizes and the talus slope angle sometimes falls to 10° to 20° as shown between Points B and C. Point C is the base of the talus deposit. Beyond this point the slope is no longer completely covered by talus particles. The average talus angle is marked as β_1. In this paper, the surface to the right of Point C is termed the "substrate surface", consisting of material and landforms pre-dating the talus

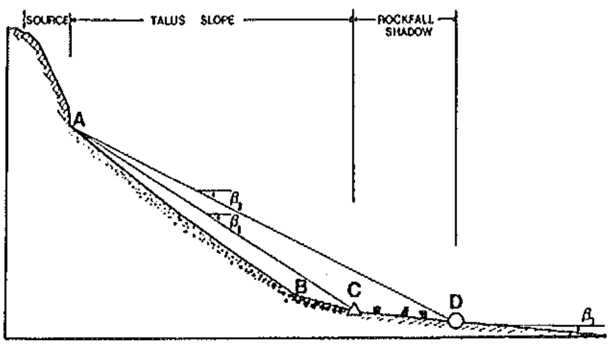

Figure 1. Schematic diagram of the characteristic rockfall path profile. A-C is the talus slope with mean angle β_1 and C-D is the rockfall shadow with a shadow angle β_2, β_3 is the substrate angle.

deposits. That part of the substrate surface covered by scattered large boulders which have rolled or bounced beyond the base of the talus (C-D in Figure 1) is referred to here as the rockfall "shadow". It represents the true danger zone of the rockfall path, since while the rockfall hazard is obvious on the talus surface itself, in the shadow area it sometimes may not be apparent. We define the "shadow angle" as the angle between the outer margin of the shadow and the apex of the talus slope (β_2 in Figure 1).

A characteristic example of a rockfall shadow located on a river terrace in southwestern British Columbia is shown as Figure 2. The distal part of the shadow often contains only very few boulders which are sparsely distributed on the surface. The probability of new rockfall fragments entering the shadow varies from site to site but must necessarily be extremely low since otherwise the shadow area would be covered completely by talus fragments.

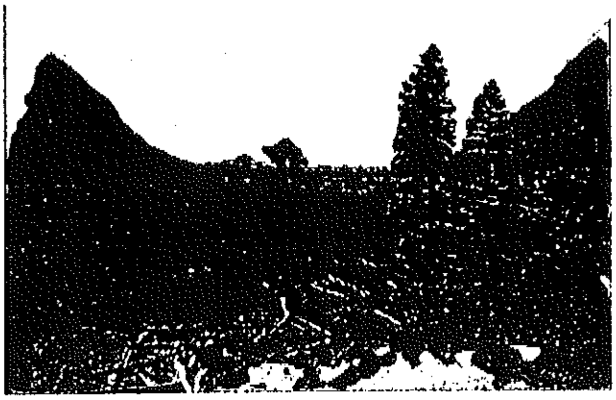

Figure 2. An example of a typical rockfall shadow associated with talus slopes in the Similkameen Valley, British Columbia. The boulders lie on a river terrace surface.

EVALUATION BASED ON GEOLOGICAL EVIDENCE

In some cases, it is possible to ascertain the past behaviour of a rock slope over a long period on the basis of geological evidence. Such information can then be extrapolated so as to predict the reach of future rockfall within a given return period.

An example is provided by the evaluation of rockfall hazard at a community in south-western British Columbia, located on a deltaic terrace. Immediately behind the community, cliffs composed of massive Eocene quartz diorite and hornfels rise to a height of 600 m. Extensive talus deposits and fields of large boulders which have rolled beyond the talus margins testify to rockfall activity, although the slopes are heavily forested and no accidents involving rockfall have been reported. The site has only been settled since the 1950's, however, and no extensive historic record is therefore available.

Figure 3 is a view from the crest of the source cliff (arrow) towards the community. The white dashed line marks a distinct, well defined limit of the boulder deposits (i.e. the edge of the rockfall shadow). No rockfall-related boulders have been found outside this line. The surface of the area outside the rockfall shadow is underlain by a deposit of cross-bedded sand containing no gravel or boulders, which is exposed in a small quarry on the left side of the photo. The sand is of deltaic origin, deposited in standing water. However, no lake has existed at the site in the Holocene. Therefore, the surface of the terrace must be at least 11 000 years old, dating back to the last stages of glacial ice retreat from the valley

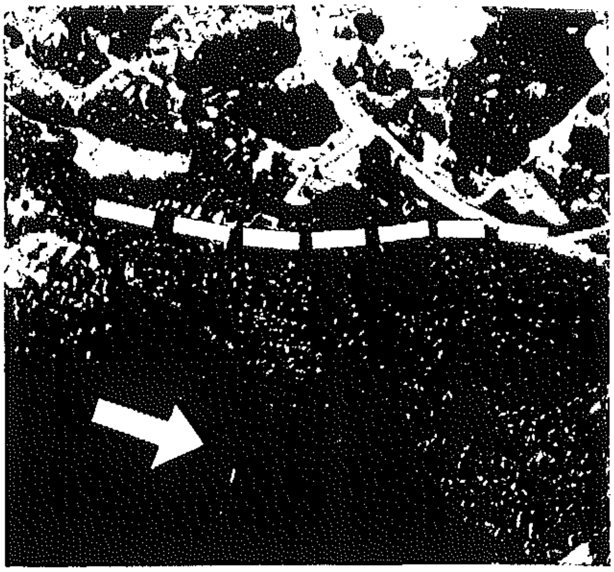

Figure 3. Oblique view of a community in southwestern British Columbia. Source cliffs for rockfall are arrowed and white dashed line is limit of rockfall boulders as discussed in text. The elevation difference between the cliffs and the white dashed line is approximately 600 m.

(J.J. Clague, personal communication, 1986). The area outside the well defined boulder deposit limits therefore has a probability of less than 1:11 000 of being reached by rockfall from the cliff in a given year.

In another example, some preliminary estimates of the probability of new rockfall fragments reaching the distal parts of the rockfall shadow shown in Figure 2 have been made. These estimates were made on the basis of exposures of Holocene volcanic ash layers in the area and indicate return periods which generally exceed 1000 years.

Not all sites provide sufficient evidence to allow such reasoning. If it were not possible to reliably date the substrate surface, if weathering conditions changed (e.g. due to deforestation or a recent major instability) or if there were boulders of glacial or debris flow origin impossible to distinguish from rockfall deposits, then this method could not be used.

EMPIRICAL EVALUATION

It has been suggested that the minimum value for the shadow angle (β_2) defined in Figure 1 should be in the range of 28 to 30° (Lied, 1977). The authors have compiled 15 profiles of rockfall paths surveyed from two areas of south-western British Columbia (Figure 4). The profiles have been plotted so as to join at the talus apex (Point A) as a common fulcrum. The points representing the limit of the shadow plot consistently just below a line inclined at 27.5°, irrespective of the height of the source cliff, length of path, or the substrate angle β_3. The data points represent locations both in the sparsely forested arid Interior of British Columbia and in the Coast Mountains where the climate is humid and where there is dense forest cover. It is noted that profiles 11 and 12 were measured in the area photographed in Figure 3.

The use of an empirical minimum shadow angle of 27.5° would consequently appear to be a useful conservative method for the preliminary estimation of maximum rockfall reach.

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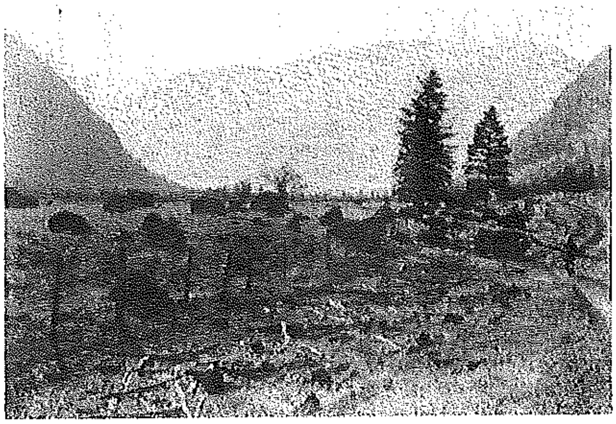

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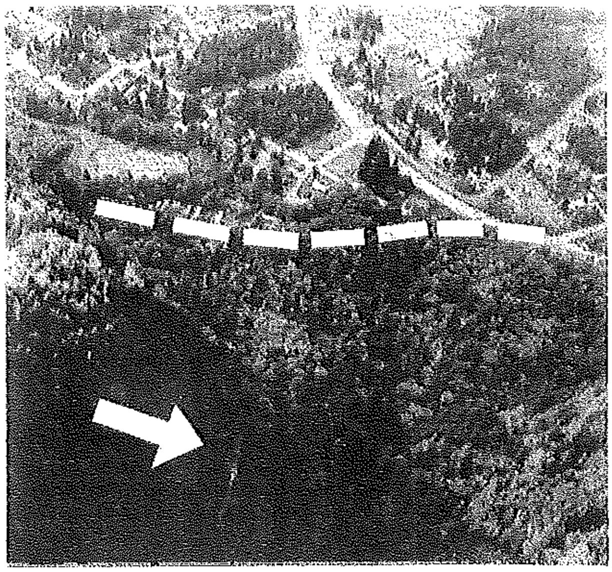

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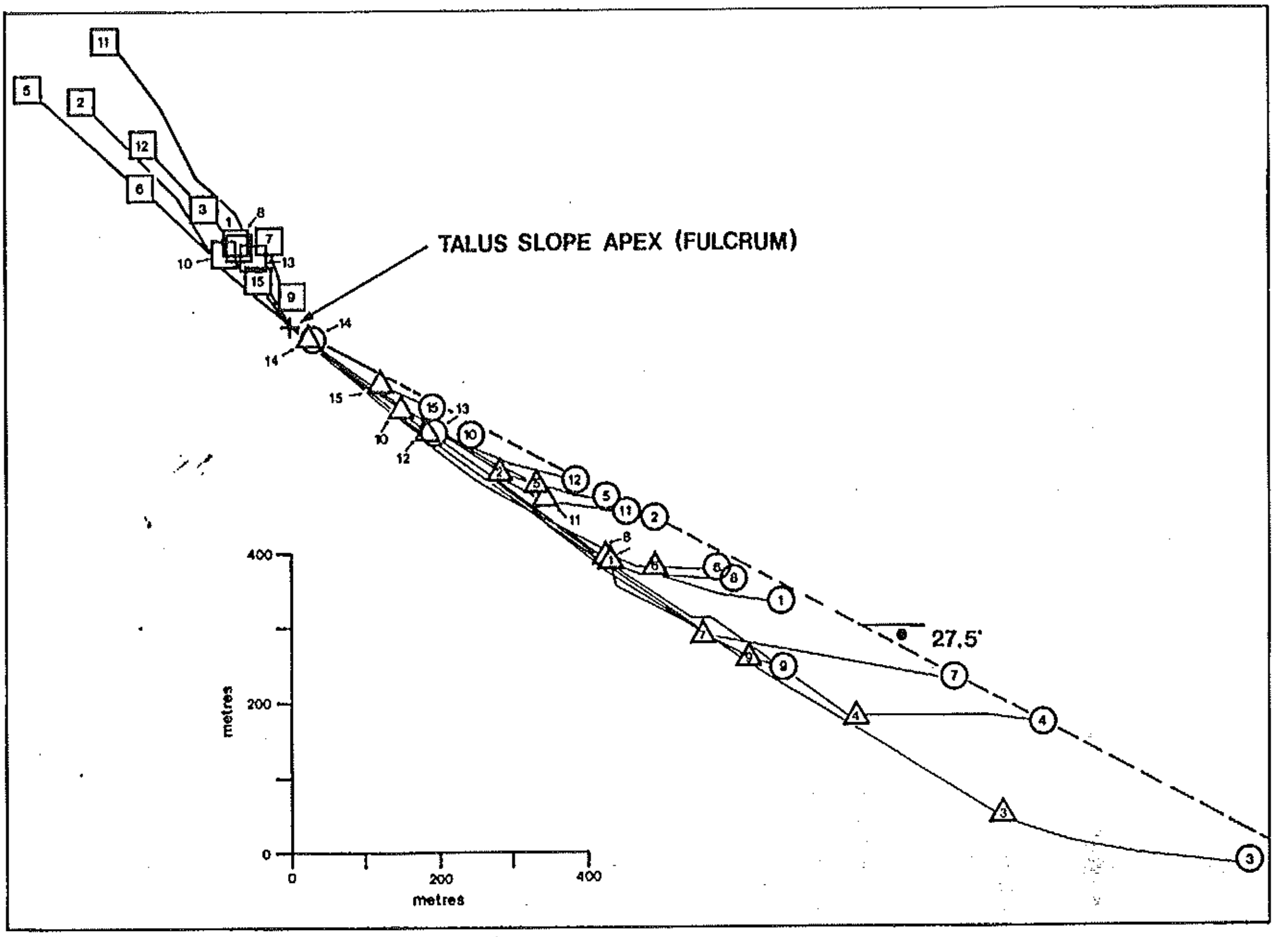

Figure 4. Profiles of fifteen surveyed rockfall paths from southern British Columbia. The profiles have been plotted with the talus apex as a common point. As in Figure 1 triangles designate the base of the talus slope and circles designate the distal margin of the rockfall shadow. The squares represent either known source areas or the crest of the source cliff.

ANALYTICAL APPROACH

In recent years, many investigators have turned their attention towards analytical computer-based methods, modelling the actual progress of a rock fragment down its path. The problem can be approached in two ways;

A. The Rigorous Method

The rigorous method was pioneered by Cundall (1971) and has been extended into three dimensions by Descoeudres and Zimmermann (1987). Actual shape and dimensions of the fragment must be assumed and all motions of the fragment are considered, including rotation. While in the air, the fragment moves on a ballistic trajectory, rotating. Upon contact with the slope surface, both translational and rotational momenta are transferred by an impact. The impulse of the impact changes both quantitites according to a very complex set of conditions depending upon the shape of the contact corner, the precise rotation angle at the point of impact, slope surface roughness and normal and frictional deformations. All of these conditions cannot possibly be taken account of and various simplifying assumptions must be made.

B. Lumped-Mass Method

In the lumped-mass approach, the fragment is considered as a single point with mass m and velocity $\underline{v}$ (where the underlining signifies a vector quantity). The point moves on a ballistic trajectory while in the air (air resistance is generally neglected). Upon contact with the slope, the normal component of velocity is reversed and reduced by a coefficient k_n (normal restitution coefficient) and the tangential velocity component is reduced by k_t (tangential restitution coefficient). No attempt is made to keep track of the rotational momentum. The two restitution coefficients are taken as bulk measures of all the impact characteristics, incorporating deformational work, contact sliding and transfers of rotational to translational momentum and vice versa. As a result, the coefficients must depend on fragment shape, slope surface roughness, momentum and deformational properties and, to a large extent, on the chance of certain conditions prevailing in a given impact.

Probably the first model of this type was developed by Piteau and Clayton (1977), followed by Azimi et al. (1982) and others. A similar program was developed by the present authors with the aim of calibrating the selection of the restitution coefficients empirically by means of field observations of large boulder runout. This work is under way at present and only partial results can be presented here.

ROCKFALL MOVEMENT MODES

As a first approximation, constant values of the two restitution coefficients can be assumed for a given fragment path. It is of interest to note the energy changes caused by collisions. While in trajectory,

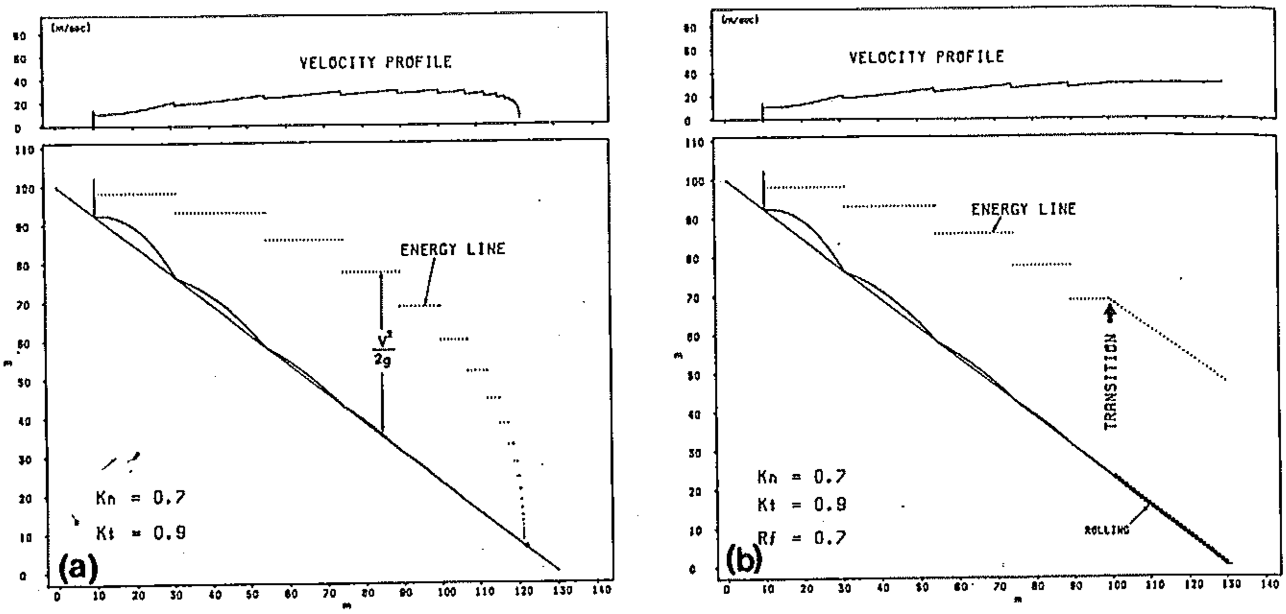

Figure 5. (a): A fragment path simulated using constant restitution coefficients throughout its length. (b): A fragment path simulated using constant restitution coefficients as in (a) but with a transition to the rolling mode. No deposition occurs on the slope. K_n=normal restitution coefficient, K_t=tangential restitution coefficient, R_f=rolling friction coefficient.

the fragment has a constant energy "head" equal to:

$$E = z + \frac{V^2}{2g} \qquad \text{Eqn. (1)}$$

where V is the length of the velocity vector and z is the fragment elevation. After an impact, the velocity component normal to the path is reduced by a ratio k_n and the tangential by k_t. It can be shown that the resulting incremental loss of energy is:

$$\Delta E = \frac{V^2}{2g}\left[\left(\frac{k_t^2 + k_n^2 \tan^2\alpha}{1 + \tan^2\alpha}\right) - 1\right] \qquad \text{Eqn.(2)}$$

where α is the angle of incidence prior to the impact. Thus, the kinetic energy is reduced in each impact by a ratio ranging from k_t^2 for very flat trajectories, through $(k_t^2 + k_n^2)/2$ for 45° impacts to k_n^2 for steep trajectories approaching the perpendicular. The "energy line" resulting from plotting the relationship in Eqn. (1) appears as a series of steps, separated by horizontal lines the length of which equals the trajectory length ΔL. When the ratio $\Delta E/\Delta L$ is less than the tangent of the slope angle, the fragment accelerates continuously and the energy line rises above the path as shown in the upper part of Figure 5a. When the ratio becomes greater than the slope gradient, the fragment decelerates and the trajectories rapidly become shorter as shown in the lower part of the figure. Deposition of the fragment then occurs.

The model described above conflicts with field observations of rockfall deposition. In reality, a reasonably equi-dimensional rock fragment steadily gathers rotational momentum in its progress down the path. As the bounces become shorter, their height becomes less and the angle of incidence becomes close to zero. At the same time, the tangential restitution coefficient must increase, as the particle rotation velocity adjusts to the velocity of flight. The result is a gradual transition to a rolling mode of motion during which there is nearly constant contact between the fragment and the slope, and the slope of the energy line is inclined at an angle equal to the rolling friction angle. As shown in Figure 5b, in the present computer model, a transition into rolling mode is made when the ratio $\Delta E/\Delta L$ becomes greater than the rolling friction coefficient, i.e., the rolling movement mode becomes more efficient than the bouncing mode. When there is a change in path slope, such as at the crest of a small cliff, the fragment may temporarily move back into trajectory.

When used with constant restitution coefficients, the model must be considered as a representation of an optimal path, in which each collision encounters an ideal roughness inclination. This actually occurs only in the case of a very small minority of fragments. The computer model has the ability to choose the restitution coefficients from a specified range at random in each impact, thus allowing for a Monte Carlo simulation of the distribution of runout distances.

For long slope segments which have slope angles of 45° and below, the present model generally predicts rockfall fragment paths which are dominated by rolling movement. This is exemplified by the long travel paths simulated in the Hedley and Sunnybrae examples below, and it is in agreement with the empirical observations of Ritchie (1963). Under such circumstances the variation, and even the absolute value, of the restitution coefficients are of secondary importance, compared to the magnitude of the chosen rolling friction coefficient. In probabilistic studies of such paths, the rolling friction coefficient will also have to be considered as a random variable, influenced by numerous unpredictable factors.

EXAMPLES OF ANALYSIS

As an initial step in the calibration of the computer model, three case histories of actual rockfall accidents have been analyzed. Each analysis used constant restitution coefficients as discussed above. Data used in the analysis were obtained from field observations, topographical surveys, coroner's documents, eye-witnesses and historical photographs.

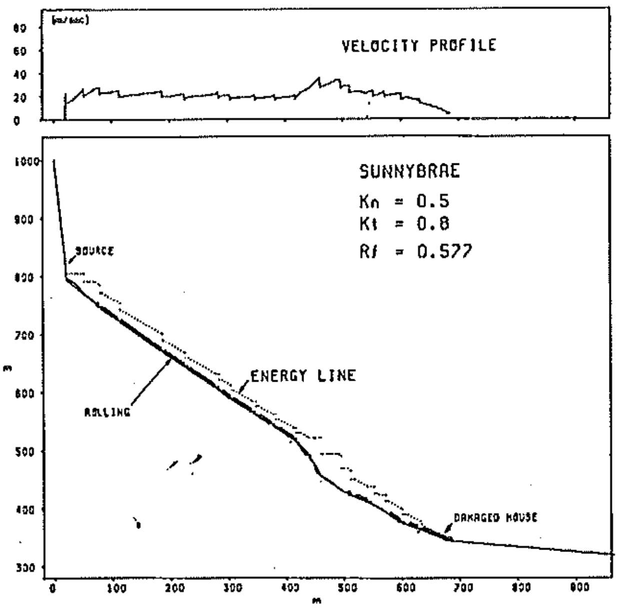

Figure 6. Simulation of the rockfall incident at Sunnybrae, British Columbia, November 23, 1983.

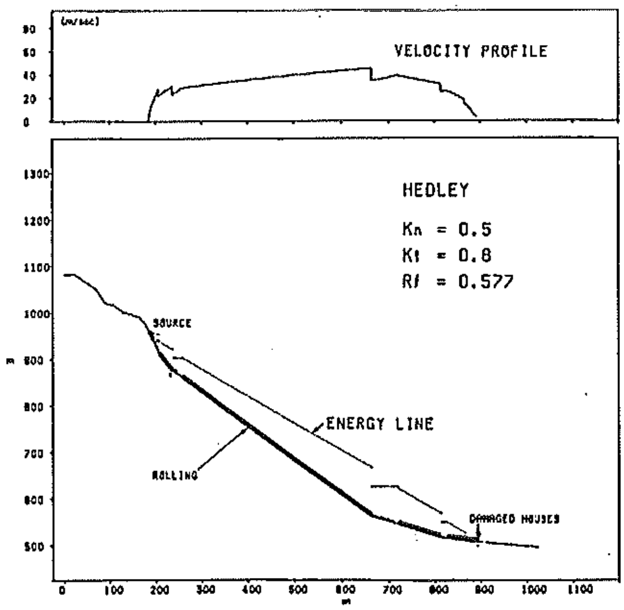

Figure 7. Simulation of the rockfall incident at Hedley, British Columbia, January 17, 1939.

Sunnybrae, British Columbia

The first case analyzed occurred on November 23, 1983 in a small community in the British Columbia Interior. The profile of the rockfall path is shown in Figure 6. A wheel-shaped boulder of metamorphosed limestone approximately 6 x 6 x 2 m detached near el. 820 m along exfoliation joints. It fell approximately 25 m vertically and then began rolling in a straight path down a slope of 32° to 34°. The sparsely forested slope is covered by a veneer of very fine weathered talus derived from weak schistose units underlying the limestone cap. When the authors examined the site four years after the event, it was still possible to trace almost continuous marks of rolling on the talus surface, appearing as a trench approximately 0.5 m deep and 2 m wide. The trace was interrupted occasionally by short bounces. Several longer bounces occurred at and below a cliff, near el. 500 m, before resumption of rolling just above the inhabited area. The boulder partially demolished a house, killing two persons, and came to rest with an equivalent shadow angle (i.e. the angle between the boulder and the apex of the talus slope) of 34°.

The computer simulation summarized in Figure 6 is in general agreement with the observed behaviour. The short periods of bouncing in the central part of the path result from minor change in slope angle. As noted earlier, the fragment behaviour is strongly dominated by the rolling friction parameter, so that the assumed collision model plays a secondary role.

Hedley, British Columbia

A rockfall struck the mining community of Hedley in the southern Interior of British Columbia on January 17, 1939. The profile is shown in Figure 7. The source was a wedge failure along a faulted contact between massive metamorphosed limestone and highly fractured basalt. Approximately 5000 m^3 of limestone began sliding on a surface inclined at 52°. It disintegrated into a number of large isolated boulders and reached the apex of a long, bare uniform talus slope formed of basalt fragments with a modal size of approximately 5 cm. Several of the boulders, 2 to 3 m in diameter, rolled past the base of the talus and damaged several houses, killing two persons. The deaths took place at a location with an equivalent shadow angle of 30°.

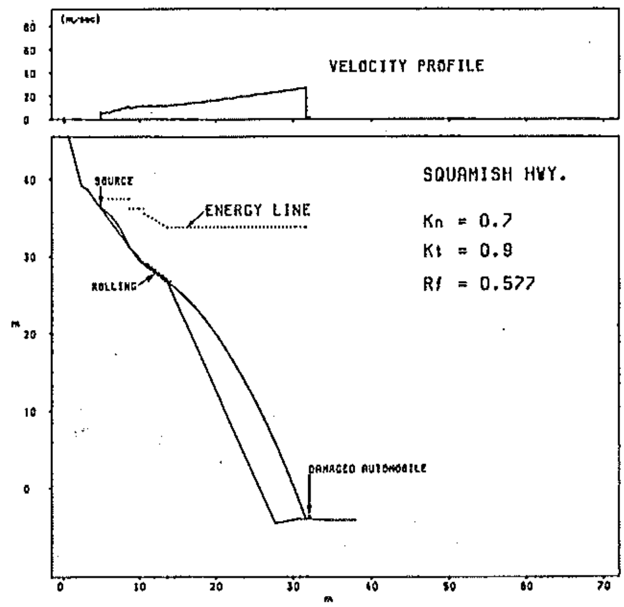

Figure 8. Simulation of the rockfall incident on the Squamish Highway, British Columbia, January 16, 1982.

The results of the computer simulation shown in Figure 7 again confirms the predominant rolling mode of movement. The analysis could for practical purposes be replaced by one based on a frictional model.

Squamish Highway, British Columbia

The third example is an accident on the Squamish Highway, north of Vancouver, on January 16, 1982. A rectangular boulder of metamorphosed tuff, approximately 0.7 x 1 x 2 m in size detached by toppling from a narrow shelf on a natural slope above a highway cut. Several short bounces occurred on bare rock. The boulder then traversed a steep snow covered shelf and fell over the edge of the steep rock cut, to land directly on the roof of an automobile. The passenger was killed instantly and the driver injured.

The analysis of the rockfall, summarized in Figure 8, uses somewhat higher restitution coefficients than the previous examples, to account for the greater expected resilience of rock to rock contacts. A small initial drop is specified, to account for the velocity gained in toppling failure. As would be expected, the path is dominated by the bouncing mode.

CONCLUSIONS

Three alternative methods of evaluating rockfall hazards have been described. The approach based on geological evidence is considered useful providing there is sufficient unambiguous evidence available to permit its use. The empirical approach based on measuring vertical angles would appear highly suitable for rapid preliminary assessments. The analytical approach, using a lumped-mass method developed by the authors, produces reasonable results, but requires much wider and more thorough calibration. This work is continuing at present.

ACKNOWLEDGMENTS

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